Basic Concepts of Electricity

- Voltage, Current, Resistance
- Voltage dividers
- Power

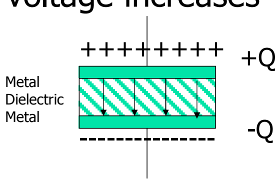
Electric Fields

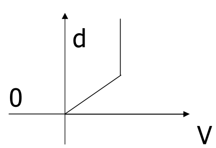
- An electric field applies a force to a charge
  - Force on positive charge is in direction of electric field, negative is opposite
- Charges move if they are mobile
- An electric field is produced by charges (positive and negative charges)
- Electric fields can be produced by time varying magnetic fields (generator, antenna radiation)

Voltage Difference

- Voltage difference is the difference in potential energy in an electric field
- $E = V/d$
- As you move closer to a positive charge the voltage increases

Capacitor (electric field constant between parallel plates)





Current

- An electric current is produced by the flow of electric charges
- Current = rate of charge movement
  = amount of charge crossing a surface per unit time
  = $\Delta Q/\Delta t = dQ/dt$ (instantaneous current)
- In conductors, current flow is due to electrons
- Conventional current is defined by the direction positive charges will flow
- Direction of electron flow is opposite to direction of conventional current

Resistance

- In materials electrons accelerate in an electric field
- Electrons lose energy when they hit atoms - lost energy appears as heat and light
- The result is that electrons drift with constant velocity (superimposed on random thermal motion)
- Resistance is the ratio Voltage/current

  $R = V/I$

Material Conductivity

- Conductors - negligible resistance
- Insulators - extremely large resistance
- Semiconductors - some resistance
- Resistors - are devices designed to have constant resistance across a range of voltages

Power

- Power = rate of energy dissipation (resistor) or production (generator or voltage source)

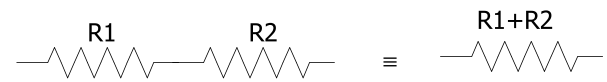
  $P = IV$

- For a resistor since I = VR and V= I/R

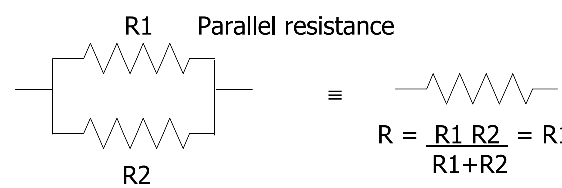
  $P = I^2 R = V^2/R$

Resistor Combination

Series resistance



Parallel resistance



$$R = \frac{R1\ R2}{R1+R2} = R1||R2$$

$$1/R=1/R1 + 1/R2$$

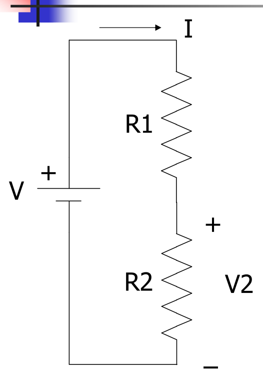
Kirchoff's Laws

- Kirchoff's voltage law (KVL)
  - The sum of voltage differences around any loop in a circuit equals 0
  - Equivalently, the voltage between two points is the same no matter what path is traversed
- Kirchoff's current law (KCL)
  - The nett current into a junction in a circuit is 0

Applying KVL and KCL

- Need to assign reference directions for voltage and current
- When applying KVL and KCL need to take care of the correct sign (+, -) when adding voltages around a loop (KVL) or currents into a node (KCL)

Voltage Divider



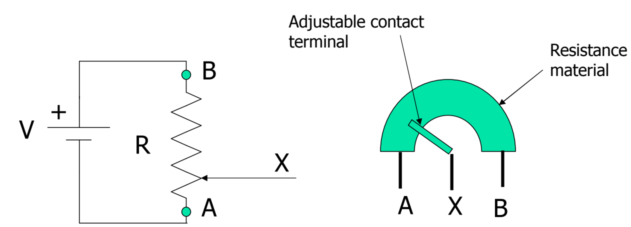
$$V2 = \frac{V\ R1}{R1 + R2}$$

<u>Solution:</u>

<u>Goal: Find V2 given V</u>

- Find V2 in terms of I
- Current through R2 in terms of I
- Voltage across R1
- Find voltage across R1 and R2 using two different methods

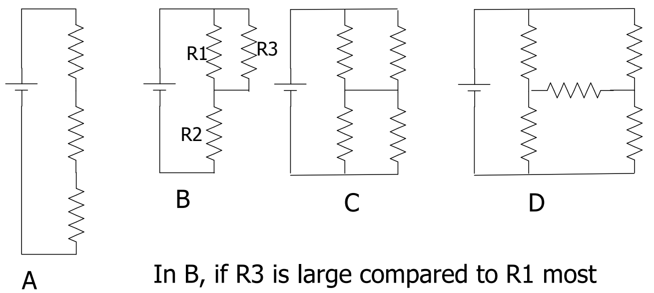
Potentiometer (Variable Resistor)



VX = V * Distance AX/Distance AB
(linear potentiometer)

A trimpot is a small variable resistor mounted on a printed circuit board that can adjusted by a small screwdriver to make semi-permanent adjustments to a circuit

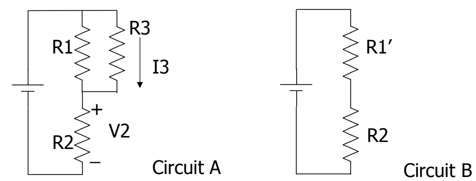
Which are voltage dividers?



In B, if R3 is large compared to R1 most current flows through R1 and R1,R2 is almost a voltage divider

Equivalent Circuits

- Circuits not identical but from some perspective behave the same
- e.g. Circuit A and B are not identical but by considering R1 and R3 in parallel and making R1' = R1||R3, they are equivalent in determining V2
- Not equivalent in determining I3 but solving circuit B can help to find I3



Input Transducers

- These are devices that produce electric signals in accordance with changes in some physical effect e.g. convert temperature, light level to a voltage level or resistance
- e.g. microphones, strain gauge, photo-detectors, ion-selective membranes, thermistors
- Sometimes the definition of transducer is that of a device that converts non-electrical energy to electrical energy

Output Transducers

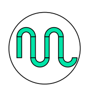
- Devices which convert an electrical quantity into some other physical quantity or effect e.g. relay, loudspeaker, solenoid

Light Dependent Resistors (LDRs)

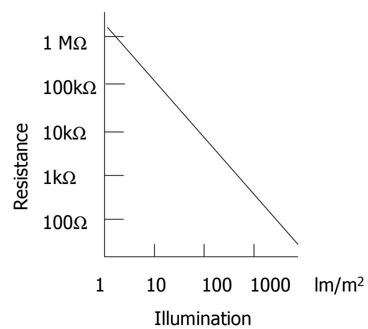
- Devices whose resistance changes (usually decreases) with light striking it
- (also called photocells, photoconductors)
- Light striking a semiconducting material can provide sufficient energy to cause electrons to break away from atoms.
- Free electrons and holes can be created which causes resistance to be reduced

LDRs

- Typical materials used are Cadmium Sulphide (CdS), Cadmium Selenide (CdSe), Lead Sulphide
- With no illumination, resistance can be greater than 1 MΩ (dark resistance).
- Resistance varies inversely proportional to light intensity.
- Reduces down to 10-100s ohms
- 100ms/10ms response time



CdS LDR
Top view

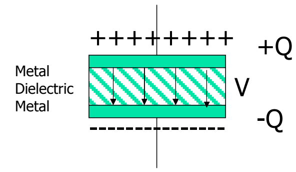


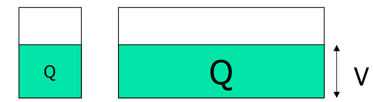
- LDRs have a low energy gap
- Operate over a wide wavelengths (some, into infrared)
- Indium antimonide is good for IR. When cooled is very sensitive, used for thermal scanning of earth's surface

Capacitors

- A component constructed from two conductors separated by an insulating material (dielectric) that stores electric charge (+Q, -Q)
- As a consequence there is a voltage difference across the capacitor, V
- Capacitance = C = Q/V
- The dielectric material operates to reduce the electric field between the conductors and so allow more charge to be stored for a given voltage

Bucket analogy



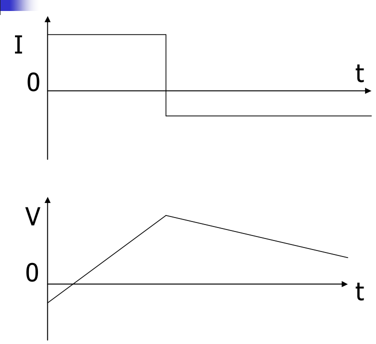


C = Q/V

(Q = CV)

A small bucket (capacitor, C) holds less charge (Q) for given level (voltage V) than a large bucket

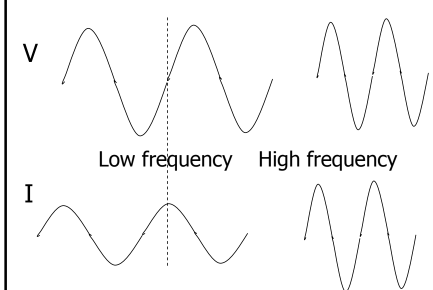
Charging a Capacitor



The bucket analogy can be used to describe capacitor charging

When current flows in at a constant rate the voltage increases linearly and vice versa for current flowing out

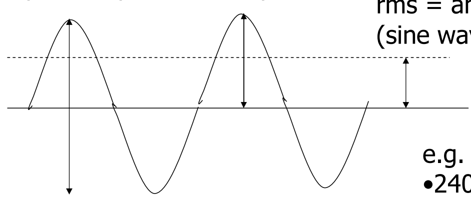
Frequency dependence



Voltage changes fastest when current is greatest

To get the voltage to swing the same amount at a higher frequency requires the current amplitude to be larger since there is less time to change the voltage by the same amount

Describing AC Voltage and Current

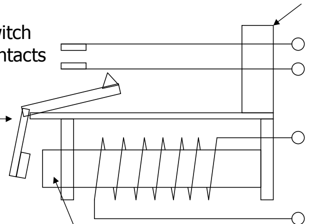


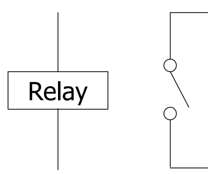
e.g. Mains voltage
•240 V(RMS)
•339 V(amplitude)

Average power = RMS voltage x RMS current
For capacitor V/I = $1/2\pi f = X_C$= Capacitor reactance

Relays

- A relay is an electromechanical switch used to switch other circuits on or off, usually carrying higher current than the relay coil itself
- Relays offer complete isolation from the circuit they control
- They enable a computer or logic circuit to control motors and other main-operated equipment
- (Adapted from Lofts et al. "Jacaranda Physics 2", 1998, John Wiley & Sons)

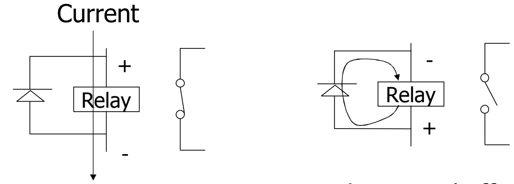




* Normally closed (N/C) contact also available

Relays

- The relay magnetic coil may operate off AC or DC voltage
- In DC use a reverse biased diode to dissipate energy when magnetic field collapses (turn relay off) - otherwise a very large and damaging back emf will be produced

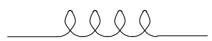


Relay energised

Relay turned off

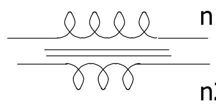
Related devices

- Solenoid - linearly actuates a rod shaped device that can be used to control water valves or air-operated systems
- Inductors - resist current flow at high frequencies



$X_L = 2\pi fL$

- Transformers



v1/v2 = n1/n2

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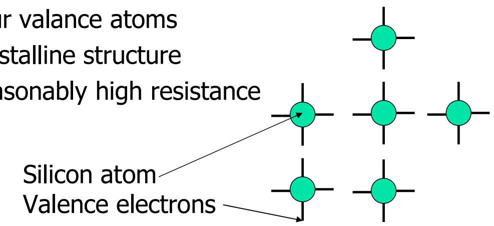
Semiconductors

- Silicon is used as an example (other semiconductors include Germanium, Gallium Arsenide, Gallium phosphide, indium arsenide, indium phosphide)
- Pure silicon (intrinsic semiconductor)
  - Four valance atoms
  - Crystalline structure
  - Reasonably high resistance



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Electrons and holes

- Due to thermal energy some electrons in the valance shell become free
- Create:
  - One free electron +
  - One hole in the valence band that can be filled by electrons from the valance band in an adjacent silicon atom
- Current in silicon can flow due to both movement of electrons and holes

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- The reverse process to hole-electron pair creation is called recombination
  - Occurs when a electron and hole meet
  - Facilitated by traps and recombination centres at deformities in crystal
- By adding impurities extra holes or electrons can be introduced - extrinsic semiconductors

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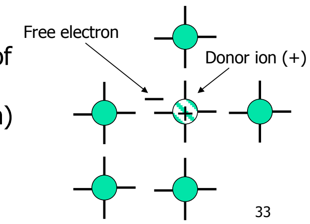
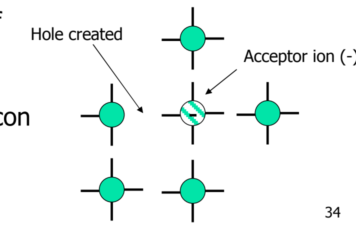
n-type silicon

- Add donor impurities (e.g. Phosphorus, arsenic, indium) with 5 electrons in the valance band
- As only four electrons can bond with neighbouring silicon atoms one free electron is left
- Increases concentration of free electrons
- Reduces concentration of holes (due to increased chance of recombination)
- Resistance reduced



- p-type silicon is created by adding acceptor impurities which have three valance electrons (e.g. boron)
- This leaves an unbound valance electron in an adjacent silicon atom creating a hole
- Increases concentration of holes
- Reduces concentration of free electrons
- P-type silicon has lower resistance than pure silicon

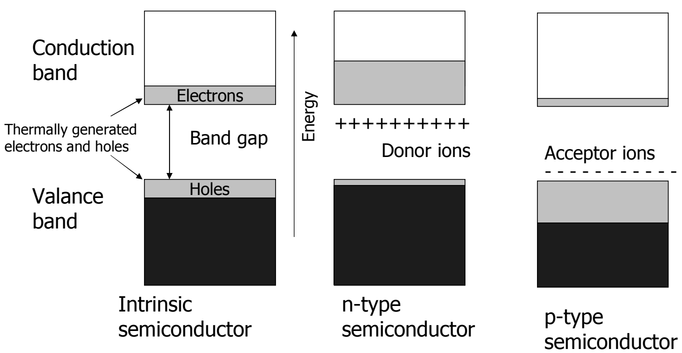


- n_i = concentration (number/m^2) of electrons in pure semiconductor
- p_i = concentration of holes in pure semiconductor
- n = concentration of electrons in doped semiconductor
- p = concentration of holes in doped semiconductor
- $(n_i)^2 = np$
- In n-type semiconductor the concentration of electrons is increased and the concentration of holes is decreased
  - electrons are majority carriers
  - holes are minority carriers
- In p-type semiconductor the concentration of holes is increased and the concentration of electrons is decreased
  - holes are majority carriers
  - electrons are minority carriers

Energy levels and bands

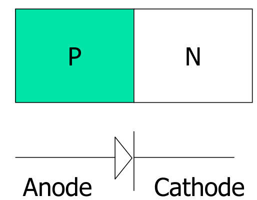
- In a single silicon atom the valance electrons are at given energy level
- In a crystal, due to Pauli exclusion effect, only two electrons can exist at same energy level (they have opposite spin)
- The single energy level splits into bands of closely spaced energy levels

Energy bands



Diodes

- If a piece of n-type silicon and p-type silicon are joined directly together a diode (di - electrode) device is created

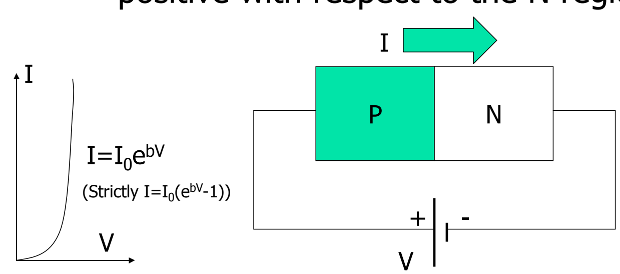


Macro-behaviour

- A diode is a device that allows current flow easily in one direction easily and allows hardly any current flow in the opposite direction

Forward bias

- Current flows easily if the P region is positive with respect to the N region

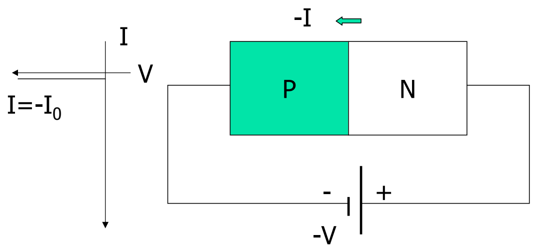


$I=I_0e^{bV}$

(Strictly $I=I_0(e^{bV}-1)$)

Reverse bias

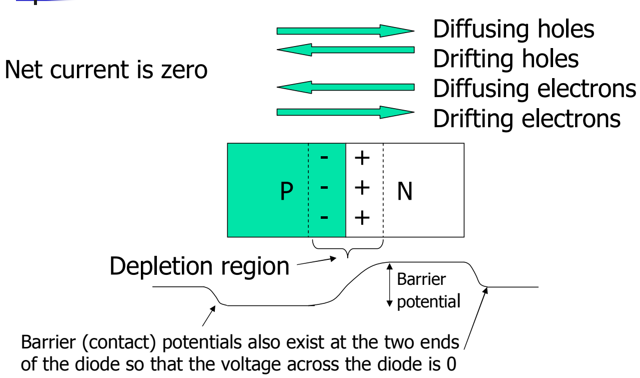
- Current hardly flows if the P region is negative with respect to the N region



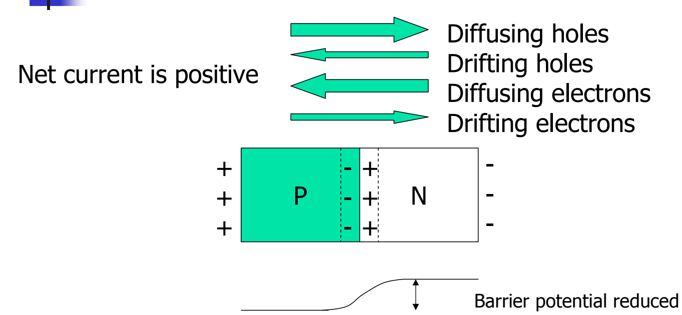
Micro-behaviour - unbiased case

- When P and N region join:
  - Electrons diffuse from the N region to the P region leaving exposed positive donor ions
  - Holes diffuse from P region to N region creating negative acceptor ions
  - This creates a depletion region around the P-N junction with no free electrons and holes
  - The charge around the junction counteracts further diffusion and applies an electric force to cause diffused holes and electrons to drift back to where they came from

Unbiased Diode



Forward biased diode

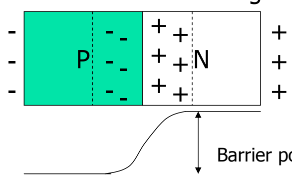


Forward bias lowers the barrier potential making it easier for holes and electrons to diffuse across the junction

Reversed biased diode

A tiny reverse current flows due to thermal creation of electron-hole pairs in the depletion region (which is wider)

~0 Diffusing holes
Drifting holes
~0 Diffusing electrons
Drifting electrons

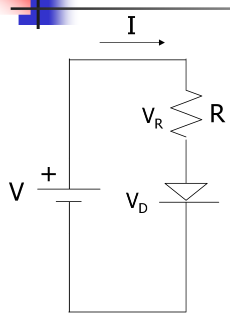


Reverse bias increases the barrier potential making it more difficult for electrons and holes to diffuse across junction

Some extra detail

- As electrons diffuse across into the p region the further they travel the more likely they will recombine with holes
  - i.e. electron current becomes hole current in the p region
  - and, vice versa with holes diffusing into the n region
- The + and - charge around the depletion region in a reverse-biased diode can be used a capacitor - useful in RF circuits

Diode and resistor circuit

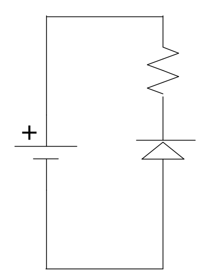


Currents and voltages determined by:
(work backwards to find V_D)
1. V_D related to I by diode equation
2. Current in resistor and diode equal
3. V_R = IR
4. voltage across diode and voltage resistor add up to voltage source V

Short cut rule of thumb, V_D is approx 0.6-0.7 volts and $V_R \approx V - 0.6$
For LEDs V_D is about 1.8 - 4.0 V, depending on colour

Forward biased diode

Diode and resistor circuit



Assume no reverse-bias current flows (ideal case)

Therefore no voltage occurs across the resistor

Therefore the full supply voltage appears across the diode

Reverse biased diode

LEDs

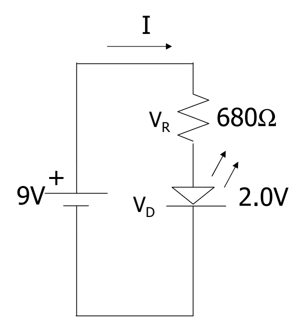
- Light emitting diode
- When an electron moves down from the conduction band to the valence band it loses energy
- In silicon and germanium the energy-momentum relationships mean that this energy is lost heat
- In gallium arsenide it produces a photon

- The light intensity is proportional to current
- Pure gallium arsenide produces infrared light
- GaAsP produces red or yellow light
- GaP produces red or green

Circuit design using LEDs

- LEDs behave just like normal diodes except that the forward bias voltages are greater (typically 1.8 - 4.0 V)
- A typical forward bias current of 10-20 mA is used.

Example



$$I = \frac{9 - 2.0}{680} = 10.29 \text{ mA}$$

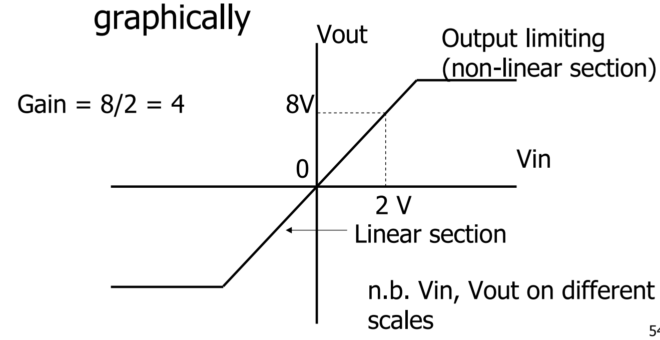
Concept of gain

- Amplifiers have an input and an output where the output voltage changes in response to the input voltage. Usually the output is an amplified version the input voltage.
- Define

  Gain = Output voltage/input voltage
- Gain encompasses the concept of proportionality
  - double input, double output; treble input, treble output etc
- When gain is less than 1 we usually use the term attenuation instead

Transfer characteristic

- Encompasses the concept of gain graphically



Decibels

- Decibels are often used to describe gain
- db = 20 $\log_{10}$ Voltage Gain = 10 $\log_{10}$ Power Gain

Volt. Gain	dB
10000	80
1000	60
200	46
100	40
20	26
10	20

Volt. Gain	dB
8	18
4	12
2	6
1.414	3
1	0
0.707	-3
0.1	-20